

WATER-TO-AIR HEAT PUMP PERFORMANCE WITH LAKEWATER

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ABSTRACT

The performance of water-to-air heat pumps using lakewater as the heat source and sink has been investigated. Direct cooling with deep lakewater has also been considered. Although the emphasis of the work was with southern lakes, many results also apply to colder climates. During the project several open loop systems, one closed loop plastic coil system, and one copper coil system were monitored. Many thermal surveys of lakes were located and performed. Computer codes were developed to determine closed loop coil length and lake thermal response to assist in design guideline development. This paper also includes recommendations concerning heat pump selection, pumping systems, piping arrangements and lake size/depth characteristics.

INTRODUCTION

Many questions concerning the suitability of lakewater for use with water source heat pumps arose during attempts to disseminate information on ground source and groundwater heat pumps. Equipment manufacturer's suggested a range of recommended coil lengths. Open loop systems were discouraged and little information concerning expected performance was available on either open or closed systems. Several systems were located with widely varying levels of home owner satisfaction. Therefore, a project was initiated to study the thermal performance of lakes, open loop heat pump systems, closed loop systems and the possibility of direct or precooling with deep, southern lakes.

Figures 1, 2 and 3 demonstrate primary system components. A closed loop system is shown in Figure 1. A water-to-air heat pump is linked to a copper or plastic coil submerged in a lake. Heat is exchanged to (cooling mode) or from (heating mode) the lake with the fluid circulating inside the coil. The heat pump is then used to transfer heat to or from the air in the building.

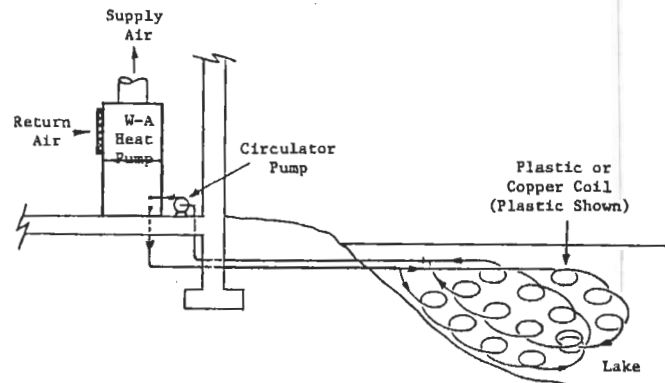


Figure 1. Closed Loop Lakewater Heat Pump

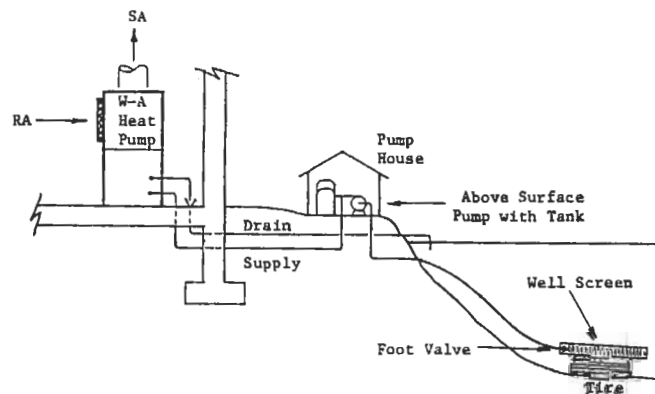


Figure 2. Open Loop Lakewater Heat Pump

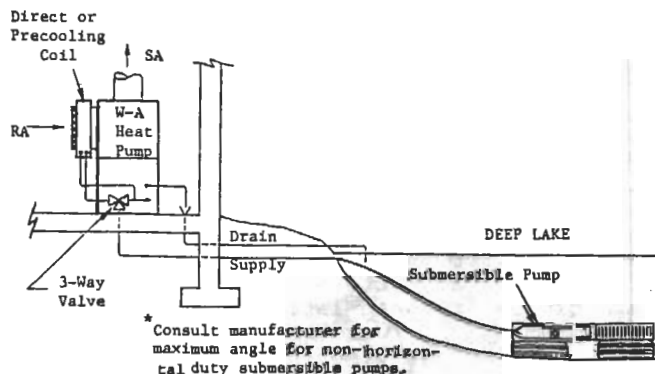


Figure 3. Direct/Precooling Lakewater System

In an "open loop" system, shown in Figure 2, water is pumped from the lake through the heat pump. It is returned to the lake some distance from the point at which it was removed. The pump is located slightly above or submerged below the lake water level.

Thermal stratification of water often results in large quantities of cold water remaining undisturbed near the bottom of deep lakes. In these cases water is cold enough to adequately cool buildings by simply being circulated through fin tube heat exchangers. A heat pump is not needed for cooling and energy use is substantially reduced. Figure 3 shows the arrangement for an open loop direct cooling system. Closed loop coils may also be used in colder lakes. Heating can be provided by a separate source or with heat pumps in the heating mode. This system also permits precooling, supplemental cooling or dehumidification should lake temperature rise unexpectedly.

References [2] and [3] discuss the results of the portion of this project that deals with the thermal response of lakes when used as a heat pump sink or source.

LAKE THERMAL CHARACTERISTICS

The project has benefitted from an extensive set of thermal surveys performed on several lakes located in North and Central Alabama [1,2]. The results indicate that in lakes deeper than thirty feet, significant thermal stratification occurs at all sites except a narrow deep lake with a high water inflow rate. In winter months, temperatures remain between 45° and 55°F [7° and 13°C] at all depths. In the summer months shallow water temperatures range between 80° and 90°F [27° and 32°C]. A sharp decline in temperature, referred to as the thermocline, is normally observed in an intermediate zone. Water temperature below this zone range between 45° and 55°F [7° and 13°C] when lake depths are greater than 30 feet [9m]. In lakes less than 15 feet deep [5m], thermal stratification in the summer is not significant. Therefore, water temperatures are almost always above 75°F [24°C] in the early summer months and above 80°F [27°C] during latter months. Summer thermal stratification occasionally occurs in lakes 20 to 30 feet [6 to 9m] in depth but typically it is not significant. Winter thermal patterns in shallow lakes are similar to deep lakes. Temperatures below 45°F [7°C] were recorded in these lakes in the early spring. These thermal profiles were verified in several lakes during this project in the Tuscaloosa-

Birmingham area. Figure 4 is included to show the range of temperatures in both deep and shallow lakes during the peak heating and cooling months.

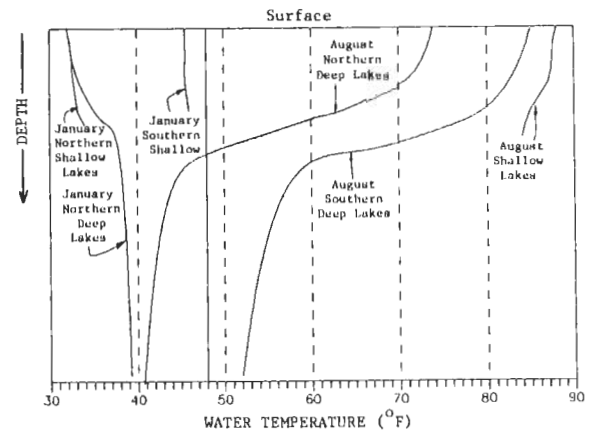


Figure 4. Characteristic Lake Temperatures

HEAT PUMPS

Proper heat pump selection is critical to acceptable system performance. Almost all water-to-air heat pumps have good cooling efficiency and capacity characteristics if entering water temperatures are held below 85°F [29°C]. Acceptable performance is realized with 85° to 95°F [29° and 35°C] entering water. Water flow rate should range between 2.5 and 3.0 gallons per minute (GPM) per ton of cooling [2.7 and 3.2 LPM/kW]. Cooling efficiency is outstanding with entering water temperatures between 55° and 75°F [13° and 24°C]. Direct cooling is possible below 55°F [13°C]. Substantial system performance benefits can also be realized by precooling heat pump entering air with 55° to 65°F [13° and 18°C] water in a fin tube heat exchanger.

However, care must be exercised in selecting a heat pump unit for heating purposes. Many of the units available through distributors are intended for use with winter entering water temperatures above 50°F [10°C]. With these units heating capacity with entering temperatures characteristics of lakewater is poor. This can be seen by comparing the Brand X heat pump with others listed in Table 1. Therefore, only units rated for operation with 45°F [7°C] and lower should be used. Flow rates near 3.0 GPM per ton of heating [3.2 LPM/kW] will insure water outlet temperatures above the freezing point of water, if entering temperatures are above 40°F [4°C]. Table

1 is an abbreviated performance chart for three different water-to-air heat pumps. Manufacturers provide more extensive details of heat pump performance.

TABLE 1
WATER-TO-AIR HEAT PUMP CAPACITIES AND EFFICIENCIES
9 GPM, 1200 CFM, 80°/67° EAT

	COOLING CAPACITY [1000 Btuh]	EFFICIENCY (EER) [Btu/whr]	HEATING CAPACITY [1000 Btuh]	Efficiency (COP)
EWT[°F]	65 85	65 85	45 65	45 65
Brand A	42 37	14.6 11.2	43 54	4.1 4.5
Brand B	38 34	14.6 11.5	32 44	3.3 3.9
Brand X	37 36	13.0 11.3	21 29	2.3 2.9

*Deduct 6 to 8% for closed loop system efficiency.

OPEN LOOP SYSTEM PERFORMANCE

The possibility of fouling would at first be an obvious impediment to the use of open loop lakewater heat pumps. While this problem is a real possibility, it can be dealt with effectively to insure the system is reliable and efficient. In support of this statement several points must be recalled.

1. River and lakewater have been used for decades in tube-in-shell heat exchangers and effective methods for dealing with fouling are available.
2. The critical thermal resistance in a water-to-refrigerant heat exchanger is on the refrigerant (and oil mixture) side. Only severe fouling will significantly degrade overall performance.
3. Most reliability problems occur with flow control mechanism. Many of these mechanisms can be simplified or eliminated.
4. Cleaning of the water-to-refrigerant heat exchanger is a relatively simple and inexpensive procedure in installations where water quality is poor.
5. An open loop heat pump system tested during the course of this project shows no significant loss in performance after four years of operation with minimal filtration.

Two open loop lakewater systems were monitored with a portable computer based data acquisition system during the course

of the project. The Brierfield system consists of a 3.5 ton [12 kW] low temperature heat pump and a one-half horsepower [0.37 kW] submersible pump. The piping consists of 1.25 [3.2 cm] inch PVC from a one acre [4000 m²] lake to the house. Inside the house 1 inch [2.5 cm] PVC was used. Manual flow control is achieved through a ball valve on the outlet of the heat pump. The outlet piping is 1.25 inch PVC from the house to the lake. The submersible pump is enclosed in a well screen to prevent large debris from being drawn into the system. The pump is mounted on a stand approximately one foot [0.3m] from the bottom of the lake.

The heat pump is rated to provide 38,400 Btu/hr [11.2 kW] at the winter test conditions. During the test it delivered 37,150 Btu/hr. For the summer condition it is rated at 41,900 Btu/hr [12.2 kW]. During the test it delivered 41,600 Btu/hr. Both of these results are within 5 percent.

The Alabaster home is a multi-zone structure. There are three heat pumps in the house. The unit tested has a 3.5 ton [12 kW] rating. A one horsepower [0.75kW] centrifugal pump provided water for all units. It is located in a small pump house approximately 50 feet [15m] from the pump intake. A foot valve in the lake prevents loss of suction. The lake area is 25 acres [0.1 km²] and depth is 10 feet [3m] at the pump suction.

Figure 5 shows water and air temperatures for the Brierfield system during the very dry summer of 1988. Lake temperature remained at 82°F [28°C] and was unaffected by the heat input from the unit. Unit performance was very good on this 95°F [35°C] day. Heating performance during the previous winter was unacceptable because the unit was undersized. The owner took steps to reduce infiltration and duct leaks in the 150 year old home. Comfort was acceptable during the 1988-9 winter.

Figure 6 shows the heating performance of the properly sized Alabaster unit. The heat pump is well suited to winter lake temperature (similar to Brand A, Table 1) and comfortable supply air and room air levels are maintained. Even though the pump suction is only 6 feet [2m] below the surface, the water temperature was near 46°F [9°C] the entire day.

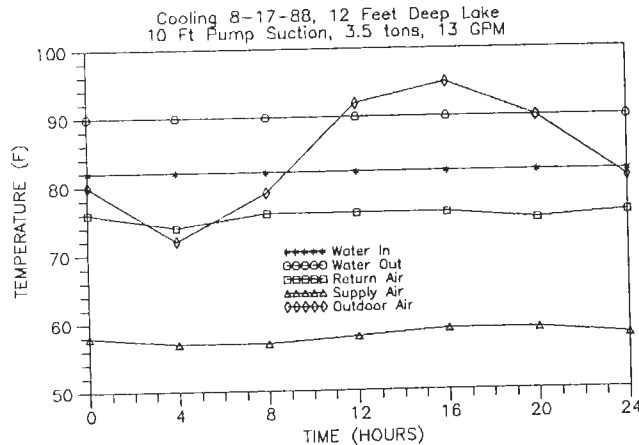


Figure 5. Summer Air and Water Temperatures for Brierfield Open Loop Lakewater Heat Pump

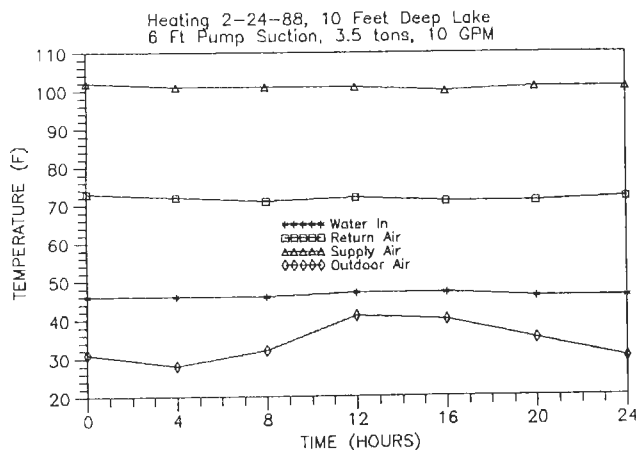


Figure 6. Winter Air and Water Temperatures for Alabastor Open Loop Lakewater Heat Pump

CLOSED LOOP SYSTEM PERFORMANCE

The closed loop lakewater heat pump system as shown in Figure 1 has two primary advantages. The most obvious is the reduced fouling resulting from the circulation of clean water (or water/antifreeze solution) through the heat pump. A less evident advantage is the reduced pumping power requirement. Closed loop systems can be designed to operate with less than 0.075 kW/ton [0.02 kW/kW]. This results from the absence of an elevation head from the lake surface to the heat pump.

There are two, or possibly three, primary disadvantages of the closed loop system. The performance of the heat pump is slightly reduced because the circulation fluid temperature degrades 4° to 12°F [2° to 7°C] when compared to the lake temperature. The second obvious

disadvantage of the closed loop system is the possibility of damage to coils located in public lakes. Thermally fused polyethylene or polybutylene loops would be much more resistant to damage than copper, glued plastic (PVC) or tubing with band clamped joints. The third possible disadvantage is fouling on the outside of the lake coil. This would be a possibility in murky lakes or in installations in which coils are located on or near the lake bottom. In the systems monitored during the course of this project, the second and third disadvantages did not affect performance. However, the first disadvantage, temperature degradation, had a significant impact.

Two closed loop heat pump systems were monitored during the course of this project. Performance reports from other systems indicate similar behavior. The Lake Tuscaloosa home is heated and cooled by a 3 ton [10.5 kW] water-to-air heat pump. The unit is linked to a 1000 feet, 1 inch [300m, 2.5 cm] polybutylene coil. The coil has 4 parallel loops and is located in 8 feet [2.5m] of water. Two 600 feet, 1.5 inch [180m, 4cm] headers connect the coils to the heat pump. Approximately one-half of the header is buried in soil and one-half is submerged in the lake. Water flow is provided by two 1/12th horsepower [60w] circulation pumps in series. No auxiliary heating was installed.

Figure 7 shows the results of a test performed on the system during a period when the outdoor air temperature was 96°F [36°C]. The temperature of the water entered the heat pump at 85°F [29°C] during the beginning of the test and rose to a value of 96°F after 30 minutes. The unit was able to maintain the indoor air

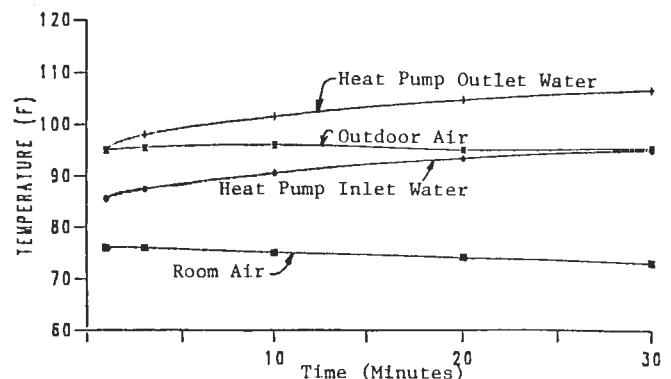


Figure 7. Closed Loop Polybutylene Heat Pump System Temperatures-Cooling

at 75°F [29°C]. The lake water temperatures around the coil and header ranged between 83° and 90°F [28° and 32°C]. Because of the warm entering water temperatures the unit's capacity and efficiency were comparable to a similar sized air source heat pump.

Figure 8 shows the results of a heating test performed on this unit. During a six hour period when outdoor air temperature ranged between 25° and 35°F [-4 and 2°C], the fluid temperature entering the heat pump was between 43° and 48°F [6° and 9°C]. The unit maintained the indoor air temperature [65°F] to the home owners desire. However, supplemental heat would have been required to maintain a higher set point. Note that entering fluid temperature was slightly above the average lake temperature at the beginning of the test. This indicates some heat was being supplied by the ground around the headers. It should be noted that the heat pump unit selected was not intended for operation with low entering water temperatures. Significant capacity and efficiency improvements over air source system can be realized with water temperatures above 40°F [4°C]. This system did not significantly capitalize on this possibility.

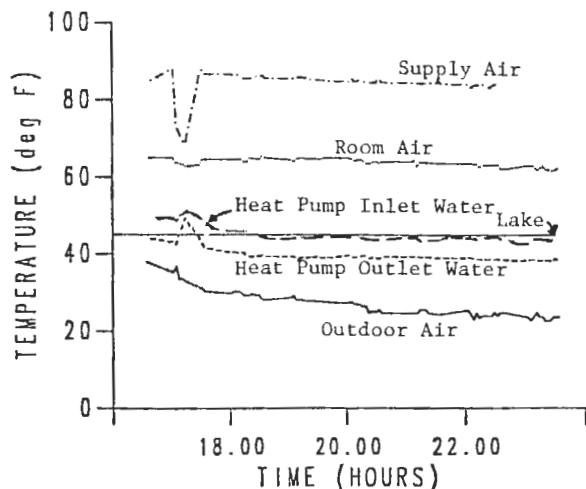


Figure 8. Closed Loop Heat Pump System Temperatures-Heating

The home owner was comfortable. However, he lived alone in the structure. A typical family would increase the cooling load beyond the unit capacity. Most home owners would require a higher indoor air temperature in the heating mode. Therefore, supplemental heat would be necessary.

The Pinson home was monitored only in the cooling mode. The water flow rate of the system was too low for the unit to

operate during periods of high heating requirements. The system consists of a five ton [18kW] water-to-air heat pump for the lower zone in the home and a 2.5 ton [9kW] unit for the upper zone. Flow through the heat pumps is a parallel arrangement and they are both connected to a copper lake coil. The coil is made of 25, twenty-foot [6m] lengths of hard drawn copper pipe connected in parallel to one inch [2.5 cm] copper headers. The coil was originally in water at a depth of 20 to 25 feet [6 to 8m]. The drought of 1988 left the coil in only 15 feet [5m] of water. The coil is connected to the heat pumps with 1.5 inch [4cm] polyethylene headers. The arrangement is shown in Figure 9.

The home owner was satisfied with the performance of the smaller heat pump in both heating and cooling. Flow rate through this unit is 4 GPM [15 LPM] when both units are operating and 5 GPM [19 LPM] when the larger unit is off. This rate borders on being too low but since the load was light in heating, the rate is acceptable.

The larger unit operated acceptably during the summer of 1987. However, entering water temperatures near 100°F [38°C] were encountered during the summer of 1988 when lake depth was 15 feet [5m]. Outlet water temperatures approached 120°F [49°C]. Water flow rate is 5.5 GPM [21 LPM] when the unit is operating in tandem with the smaller unit and 6 GPM [23 LPM] when running alone. These low rates result in higher outlet water temperature in cooling, laminar flow in the copper coils, probably blocked or low velocity in some loops, and intolerable heat pump outlet water temperatures in heating.

In addition to observing heat pump water temperatures, thermal surveys of the lake were made so that adjustments could be recommended to improve performance. The location and design of the coil made it possible to determine the extent of local hot spots in the water near the coil and to visually detect any significant fouling on the exterior of the tubes. Figure 9 includes results of two thermal surveys in the water near the coil. The unbracketed values are temperatures observed during the late afternoon of a hot day. The bracketed values are for a second survey performed at 6:30 a.m. seven days after the first test. These surveys indicate that local heating in the lake results in a minor temperature increase [3.5°F, 2°C] near the center of the coil to almost negligible increases near the perimeter. Cooling at the lake surface and thermal diffusion during the night results in no observable difference in

water temperature near the coil with values at similar depths at other locations. The survey also indicates that the coil would be located in 20° to 25°F [11° to 14°C] cooler water if it had been installed slightly further away from the bank.

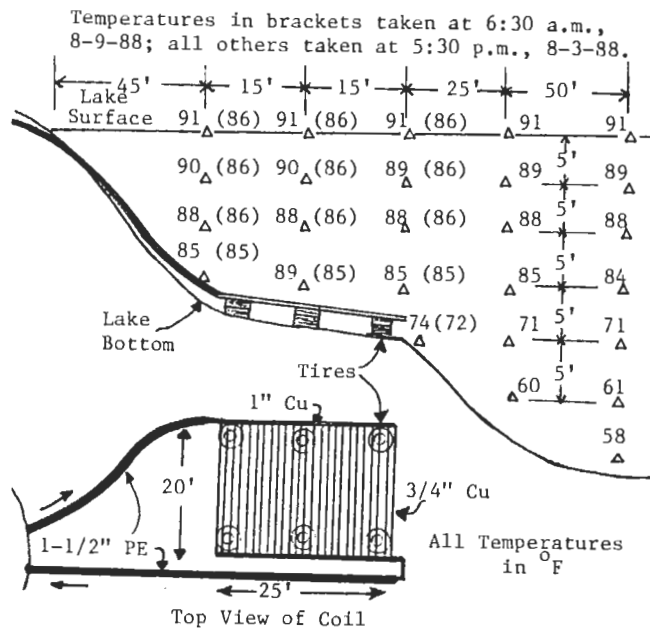


Figure 9. Lake Temperatures Near Copper Coil During High Cooling Demand Period and Off-Peak Period

DIRECT COOLING WITH LAKEWATER

As previously discussed direct cooling with deep lakewater is possible in summer months in the south. Most deep lakes contain large quantities of water below 50°F [10°C] the entire year. Submersible pumps (or above surface centrifugal pumps) can provide water through insulated pipes into the tube side of water-to-air heat exchangers. Indoor air is circulated over the finned exterior surface of the heat exchanger and is cooled and dehumidified. The slightly warmer water is returned to the lake at some distance from the original intake point. The benefit of this system is that a compressor, which consumes 70 to 80% of energy used by a standard air conditioner, is not activated. Properly designed direct cooling lakewater systems should have EERs of approximately 30 Btu/whr [COP=9.0].

An important point in direct cooling system design is to recognize that entering water temperatures must be less than 55°F [13°C]. Warmer water will not

be able to be used to sufficiently dehumidify indoor air. Even when the water is above 50°F [10°C], air side velocity must be very low in order to permit dehumidification. Water between 55° and 62°F [13° and 17°C] can be used for pre-cooling air to increase water-to-air heat pump performance. This scheme requires both a water-to-air heat exchanger and heat pump. The cool water and return air are first circulated through the heat exchanger. The air is pre-cooled (no dehumidification) before entering the heat pump. The additional cooling capacity in the heat exchanger improves the overall system performance without an increase in power requirement. Kavanaugh [5] has shown a 20% improvement in the capacity and efficiency of a water-to-air heat pump by pre-cooling with 62°F [12°C] water.

A direct cooling system was tested in a home on Lake Tuscaloosa. The unit was designed for 52°F [17°C] entering water temperature. Testing was performed with a microcomputer based data acquisition system and periodically with portable test instruments. Figure 10 shows the water and air temperatures for the system on a typical cooling day. Note how closely the outlet air temperature approached the water temperatures because of the large coil. Latent cooling was acceptable with the 52°F [11°C] water. The owner was very pleased with performance, comfort and operating cost.

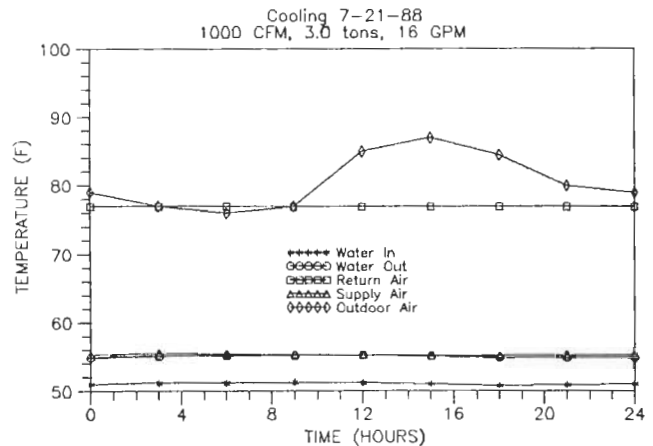


Figure 10. Air and Water Temperatures for Lake Tuscaloosa Direct Cooling System

DESIGN

Table 2, which is included as design aid for determining water temperatures for closed loop systems results from a

TABLE 2

HEAT PUMP ENTERING FLUID¹ TEMPERATURES²
FOR CLOSED LOOP LAKE HEAT PUMPS

		COOLING		HEATING			
		Lake Temperatures					
			50	80	40	50	
Pipe Material	Coil ft/ton	Fluid Temperature Entering Heat Pump (°F)					
3/4" Cu	60		67	95	28	38	
3/4" Cu	100		61	89	33	43	
1"PE SDR 11	200		64	93	32	42	
1"PE SDR 11	300		59	88	35	45	

1. 20% E. Glycol, 3 GPM/Ton, 1 parallel coil/ton.
2. For exit temperatures at 3 GPM/Ton; add 10°F to entering temperature in cooling and subtract 6°F heating.
3. Header between coil and unit is insulated to limit temperature rise to 1°F.

computer code developed as part of the project. The basic equations of the code are discussed and developed in references [4] and [6]. The table gives expected heat pump entering fluid temperature for two coil types for two (each) typical coil lengths. Entering water temperatures are given for each coil for four different lake temperatures (two for cooling, two for heating) that are representative of deep, shallow, northern, and southern lakes.

Table 2 can be used in conjunction with plots similar to Figure 4 to estimate required coil length for acceptable operation. Consider a deep lake with 50°F [10°C] water in January. Table 1 indicates the Brand A heat pump will deliver 43,000 Btu/h [12.6 kW] if entering water temperature is 45°F. Table 2 suggests 300 ft./ton of 1 inch [2.5 cm] polyethylene coil is needed to provide 45°F EWT in a 50°F lake. This system would therefore require 1050 ft. [320m] of coil (three or four parallel loops) and 10.5 GPM [40 LPM] to meet the requirements specified by Table 2. The table can also be used to calculate required lengths in lakes with temperatures slightly different than 40° or 50°F [4° or 10°C] and for cooling mode operation.

The performance of an open loop coil can be more easily predicted since EWT will be near the lake temperature. However, the unit efficiencies shown in Table 1 are typically reduced 15 to 20% when pumping requirements are included.

Performance of a direct cooling coil can be demonstrated with 50°F [10°C] summer lakewater. Without a coil the Brand A heat pump will have a capacity of 48,000 Btu/hr [14 kW], a unit EER of 16.7 [COP=4.9] and a system EER of 12.9 [COP=3.9]. If a properly sized pre-cooling coil is used capacity can improve to 65,000 Btu/hr [19 kW], and system EER to 19.5 [COP=5.7]. If a properly sized direct cooling coil is incorporated system EER can exceed 30 [COP=8.8]. However, caution is required here because direct cooling coils must be large in order to properly dehumidify air. All lines from the lower portion of the lake to the coil must be insulated to prevent the water from rising above 55°F [13°C].

RECOMMENDATIONS AND CONCLUSIONS

The minimum surface area required for a lakewater heat pump system is much less than the typical rule of thumb of one acre per heat pump. Testing of the Mahan system and the simulation developed by Pezent (3) indicate the minimum is closer to 0.25 acre per 3 ton [1000 m²/10.5kW] heat pump. However, the minimum depth of 10 to 12 feet [3 to 4m] may be too shallow, especially for closed loop systems.

Deep lakes with low and moderate water inflows have sufficient quantities of water cold enough for direct cooling throughout the summer. Winter water temperatures in Southern lakes are not significantly different than shallow lakes.

In order to have an effective lakewater heat pump system, water flow rates should be near 3.0GPM/Ton (3.2LPM/kW). This applies to both open and closed loop systems.

Not all water source heat pumps will work effectively with lakewater. Winter entering water temperatures will normally be below 45°F [17°C] January through March. Therefore, the unit selected should meet the building heating load based on the expected entering water (or water/antifreeze solution) temperature. The unit should also meet the cooling load based on expected entering water temperatures. Several different units are available that have different heating/cooling capacity combinations. The designer should attempt to closely match the combination to avoid significant undersizing in heating and significant oversizing in cooling. The use of copper-nickel alloys in the water heat exchangers gives an added measure of protection with open loop systems. However, they are not

always required. A desuperheater hot water generator is almost always an effective addition, especially when factory installed.

The fouling problems that intuitively seem significant, can be effectively minimized. Testing of the Alabaster system that has been in operation for four years indicates important precautions are to provide adequate water flow rate and to place the pump intake well off the lake bottom. Observation of other systems and conversations with well screen representative have shown that a fine slot high impact PVC (ASTM D1784 or D1785) well screen is an excellent pump intake filter.

The submersible pump has several performance advantages. Since it is located in the water, no suction loss or cavitation precautions are necessary. A bladder tank and solenoid valve are unnecessary because the pump can be cycled on and off with an electric relay. A properly sized submersible pump will require 10 to 20% less power than an equivalent above surface centrifugal pump. The centrifugal pump is located above the water surface, which may be its primary advantage. Suction loss, antifreeze, and cavitation precautions must be taken.

Closed loop lakewater heat pump systems are preferred by heat pump manufacturers because of the lack of water-to-refrigerant heat exchanger fouling. Properly designed systems require 50 to 75% less pumping power than open systems. The penalty is a slight decrease in capacity, but efficiency may be improved because of the smaller pump requirements.

1. However, the slight temperatures degradation may result in critical limitations.
2. Antifreeze solutions are usually required for winter operation since heat pump outlet water temperatures approach 32°F [0°C] when inlet temperatures are below 38°F [3°C]. Many heat pumps, protected by freeze-stats or low suction pressure switches, must be modified.
3. Shallow lakes will have summer water temperatures between 80° and 90°F [27° and 32°F]. This results in entering water temperatures being 88 to 100°F [31° to 38°C]. Often this is an improvement over air source heat pumps at peaks. But the air will cool more rapidly during off peaks, while the shallow water cools only slightly. The result is a slight improvement in peak performance, but little or no improvement in average daily performance.

4. The slight degradation caused by a closed loop coil in a deep lake may raise the entering water temperature to above a value that will effectively dehumidify in a direct cooling application.

Therefore, to realize an improvement in seasonal cooling efficiency with closed loop systems, the lake should be 80°F [27°F] or lower during August. This typically translates in a depth greater than 15 to 20 feet [5 to 6m]. However, seasonal heating efficiency will be significantly improved by closed loop heat pump systems in both shallow and deep lakes. Seasonal cooling efficiency in deep Southern lakes will be significantly improved over air source units and in some cases will have better efficiency than open loop systems.

Deep lake summer temperature even in the South range between 45° and 50°F [7° and 10°C]. This is sufficiently cold enough to directly cool and dehumidify with open loop water systems. Headers to the heat pump need to be insulated and water-to-air heat exchangers are typically derated 50 to 70% of their nominal ratings [45°F EWT, 80/67°F EAT]. Pumping and piping arrangements are similar to open loop heat pump systems. A water-to-air heat pump makes an excellent heating source in combination with direct cooling systems. It can also function as an auxiliary cooling and dehumidification source should the lakewater temperature unexpectedly rise.

Closed loop coils in lakes 48°F [9°C] and below can be used for direct cooling if coil lengths are very long. If entering water temperatures are between 55° and 62°F [13° and 17°C], a precooling coil placed in the return air duct of a water-to-air heat pump can improve system efficiency 20 to 40%.

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